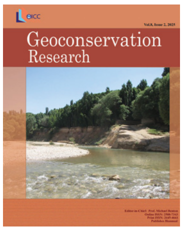

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Collaborative Cartography as a Tool for Inventory of Waterfalls in Municipalities in Southern Brazil

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Abstract

We investigate collaborative cartography as a tool for inventorying waterfalls in the municipalities of Pelotas and Arroio do Padre in southern Brazil. We aim to identify and catalog waterfalls through community participation to support the development of geotourism itineraries and promote the dissemination and environmental interpretation of these geodiversity elements. We employed a two-phase approach through online questionnaires distributed through social media platforms during the COVID-19 pandemic. The first phase (December 2020–March 2021) involved 70 collaborators who identified 17 waterfalls, while the second phase (September–October 2021) engaged 36 additional participants who contributed three new waterfall identifications. The survey instrument, titled "Cachoeiras Costa Doce Form," collected data on waterfall names, locations, and optional photographic documentation. Field validation was conducted in February 2022 using GPS technology and aerial imagery to verify collaborative mapping results and assess waterfall characteristics. Respondents identified 18 waterfalls, with four receiving the highest recognition: Imigrante (25 mentions), Arco-Íris (18 mentions), Paraíso (14 mentions), and Camboatá (14 mentions). Of the five criteria, eight waterfalls demonstrated high accessibility values, seven exhibited significant cultural connections, and eleven maintained excellent environmental preservation status. The study demonstrates that collaborative cartography effectively leverages local community knowledge to identify geoheritage elements, particularly in areas with geological-geomorphological significance. However, limitations include potential selection bias due to digital divide constraints affecting rural populations with limited internet access. The methodology has potential for international replication and contributes to sustainable geotourism development while supporting geoconservation initiatives through community engagement and scientific assessment integration.

Keywords: Geodiversity, Geoheritage, Geotourism, Volunteered Geographic Information, Collaborative Cartography

Introduction

Geodiversity, encompassing the geological variety of minerals, fossils, rocks, landforms, and physical processes that operate on abiotic elements, including pedological and hydrological phenomena (Gray 2004; Brilha 2005), is a fundamental component of Earth's natural heritage. The recognition and conservation of geodiversity elements as geoheritage has become increasingly critical in the context of sustainable development and environmental protection (Henriques & Brilha 2017). However, despite growing international recognition of geoheritage importance, significant challenges persist in developing effective geoconservation strategies that integrate scientific rigor with community engagement and sustainable tourism development.

Williams *et al.* (2020) identified critical gaps in geoconservation research and practice, highlighting the isolation of geoconservation professionals from development and management strategies of geotouristic sites, which limits the quality of scientific communication of geoheritage values to the public. Further, Gupta *et al.* (2024) demonstrated that existing research extensively evaluates tourism prospects and site assessments but falls short in delivering applied sustainable solutions necessary to promote Sustainable Development Goals (SDGs), particularly in developing accessible and cost-effective inventory methodologies.

Traditional geoheritage inventory approaches, while scientifically robust, often require substantial financial resources, specialized expertise, and extended timeframes that limit their applicability in resource-constrained contexts (Brilha 2016). These conventional methods frequently overlook local community knowledge and fail to engage stakeholders who possess an intimate understanding of geological, geomorphological and hydrological features. This disconnect between scientific assessment and community engagement is a barrier to effective geoconservation implementation.

Despite the recognized potential of collaborative approaches in environmental science, there is a significant gap in the application of collaborative cartography and Volunteered Geographic Information (VGI) methodologies for geoheritage inventory and geoconservation purposes. While Goodchild (2007) established the theoretical foundation for VGI as a paradigm where citizens act as sensors in geographic data collection, and Haklay (2013) provided frameworks for citizen science participation in geographic information systems, there has been little research on the systematic application of these methodologies to geoheritage identification and assessment.

The integration of collaborative mapping approaches with geoconservation objectives presents an opportunity to address multiple challenges simultaneously: reducing inventory costs, incorporating local knowledge systems, enhancing community engagement in geoconservation, and developing scalable methodologies for geoheritage identification. This gap is particularly pronounced in regions with significant geodiversity but limited resources for comprehensive geological surveys, such as many areas in the Global South.

Here, we investigate the application of collaborative cartography in inventorying waterfalls in the municipalities of Pelotas and Arroio do Padre in southern Brazil, to support the development of geotourism itineraries and promote the dissemination and environmental interpretation of these geodiversity elements. This is a practical example of the application of a citizen science approach in geoconservation, assessing the efficiency and accuracy of the method and its cost-effectiveness. Further, the study contributes to sustainable geotourism development by demonstrating how community-based inventory approaches can simultaneously support scientific knowledge generation, local capacity building, and tourism planning initiatives. Our study also addresses the limited attention given to hydrological geodiversity elements in geoconservation literature and contributes to the underrepresented Latin American perspective while offering methodological innovations with global applicability.

Collaborative Cartography: Use and Applications to Geoheritage

Cartography is the art and science of designing, constructing, and disseminating maps, which are characterized as flat, simplified, and standardized representations of geographical space or portions thereof, maintaining proportional relationships at specific scales (Rizzatti *et al.* 2022). Edney (2016) sees the map as a liberating representation, allowing users to select their own starting points and follow their own routes through an image, with the aim of drawing conclusions or simply locating themselves. Building on this perspective, Harley (1989) argues that cartographic documents can be understood as rhetorical constructs that should be interpreted as texts. However, maps have traditionally been approached in an uncritical manner, with insufficient analysis of their composition and epistemic foundations, resulting in oversimplified consensus regarding the definition and interpretation of cartographic documents (Harley 1989; Moraes *et al.* 2021).

The emergence and proliferation of Geographic Information Systems (GIS), coupled with the increasing technical orientation of cartography, have resulted in the reduction of artistic and critical dimensions in map production (Moraes *et al.* 2021). Harley (1989) contended that cartographic documents should be understood as cultural texts that encompass multiple interpretative possibilities. Therefore, it is important to emphasize that cartographic documents need to transcend the rules that dominate cartographic science, adopting social and historical theories, and trying to understand the mapped elements as products of a context that deviates from the standardization of cartography and geography (Harley 1989; Moraes *et al.* 2021; Paganotto 2022).

Accordingly, contemporary critical cartography conceptualizes maps as heterogeneous products resulting from cartographers' decisions and contributions throughout the entire process, from field data collection to final representation. These products reflect multiple political objectives and are grounded in diverse epistemological frameworks (Moraes *et al.* 2021).

Cartography can also be interpreted as a multidisciplinary science, as it dialogues with history, anthropology, and sociology in an overlapping manner (Moraes *et al.* 2021). Therefore, humanistic and cultural geography approaches ethnogeography with the aim of reading the inhabited place, highlighting processes and elements important for understanding it (Almeida 2018).

Almeida (2018) points out that the inhabited place can be assimilated through its representations, allowing actors to affirm that a given place can be diverse and multiple according to the perspectives of those who experience it and those who represent it. The author also notes that the ethnogeographic method presents the researcher with the perception that individuals have of the world and enables various ways of exploring and getting to know reality (Almeida 2018).

Costa (2016) states that:

> ethnogeography must move between coexistence and continuous recording in a spatiality delimited by the research interest (which is contained in the researcher's own spatial experience and must be revealed honestly as his trajectory and as a participatory subject in society), in the use of field notes and in the recording of conversations that were woven as simple everyday contacts (Costa 2016, p. 142).

In this context, collaborative cartography is an important tool for ethnographic studies in the context of critical and human geography, as it is a proposal by artistic and/or cultural groups for collective mapping. It is also an instrument that can be used in physical geography to identify abiotic elements such as rocks, fossils, watercourses and waterfalls (Cardoso 2017).

Athaydes *et al.* (2018) explains that collaborative cartography is characterized as a tool made up of the individual and social practices of each subject, which can represent the lived reality based on information originating in society. The dynamism between the map and the respective social groups highlights the transformations carried out in space and their relationship with the environment (Tavares *et al.* 2016; Athaydes *et al.* 2018).

Paulovski and Colavite (2020) state that collaborative cartography helps the communication of the various actors in society, since it is necessary for social relations to take place so that the mapping resulting from this type of cartography shows, in addition to information of a physical nature, the power relations that can occur in social groups with a high degree of interaction (Tavares *et al.* 2016).

Tavares *et al.* (2016) also point out that collaborative cartography helps communication between individuals. They express their opinions on a given research object to obtain a cartographic document prepared by several authors, known as collaborators. Communication between these collaborators can take place in person or through platforms, apps and social networks (Martins Junior 2018; Tavares *et al.* 2016). However, there must be more than two individuals for co-participation to take place. It should also be noted that this initiative is based on the theme stipulated by the producer of the cartographic content, or according to the needs of each group of collaborating users (Tavares *et al.* 2016).

Martins Junior (2018) states that collaboration through social networks to obtain cartographic products is a positive strategy for collaborative cartography and is not a recent form of intervention. Before the advance of Web 2.0, cooperation occurred in an embryonic and experimental way on digital platforms, where the interaction between the author of the information and the consumer was biased, as only the data desired by the producer was computed, which discouraged comments, suggestions and edits (Martins Junior 2018).

This was the scenario before Web 2.0 - an expression conceived to represent the second-generation World Wide Web (WWW), which offered communities and services based on internet connections - (Martins Junior 2018). Before this, there were no geospatialization tools and structures, which were necessary for collaboratively generated content to be produced and spatially reproduced (Martins Junior 2018; Martins Junior & Silva 2018).

Barbosa *et al.* (2016) point out that the union between the internet and GIS has made it possible to introduce WebSIGs, platforms available on the WWW that allow spatial data to be distributed to society in general. Applications such as NASA World Wind and Microsoft's Virtual Earth are examples of WebSIGs, as they allow operators to add and remove spatial information. However, it is not possible to acquire information and carry out analysis from them (Barbosa *et al.* 2016). Other tools, such as Mapguide, Openlayers, Mapserver and ArcGIS Online, make it possible to create and explore geographic spatial content.

Cardoso (2017) points out that this type of mapping

> [...] it follows the trend of geographic information obtained through the voluntary contribution of subjects (Volunteered Geographic Information/VGI), being one of the possibilities of a larger phenomenon on the Web which is user-generated shared content (Cardoso 2017, p. 52).

As a result, VGI has come to be seen as a content-generating tool, which is done through the GIS (Cardoso 2017). These tools make it possible to integrate the contributions of different collaborators, using detailed and sophisticated information, often held by public and private institutions, thus using the internet as a source of collaboration (Cardoso 2017). Collaborative cartography can be divided into two categories:

a) with data generated from the displacement of the actors, done manually, with the collage of multiple information collected by all the participants and (Cardoso 2017);

b) physical and digital maps, in which information is collected, sent and presented (Cardoso 2017).

This second modality, which makes use of technologies, is used as an ally for the preparation of this research, since digital collaborative cartography aims to give meaning to inhabited spaces, integrate the various collaborators, as well as mobilize and motivate the target community (Cardoso 2017; Paganotto 2022).

Internationally, collaborative approaches to geoheritage inventory have gained prominence in recent years. In the United States, the Geoheritage Sites of the Nation project by the U.S. Geological Survey has been systematically identifying geologic sites that have played significant roles in impacting society throughout history, demonstrating the value of comprehensive geoheritage inventories for national heritage management (USGS 2025). European initiatives, coordinated by EuroGeoSurveys, provide expertise for long-term management of Europe's geoheritage through international collaboration, emphasizing the importance of standardized methodologies for geoheritage assessment (EuroGeoSurveys 2024). In Italy, advances in geoheritage mapping have been developed through systematic methodologies applied to iconic geomorphological examples, providing frameworks for integrating scientific assessment with territorial planning (Coratza *et al.* 2021). Portugal has been developing unified geosite inventories through collaborative processes with international researchers, while Spain has implemented methodological proposals for geoheritage mapping in protected areas such as the Regional Park of Picos de Europa (Pereira *et al.* 2025). These international experiences demonstrate the growing recognition of collaborative methodologies as essential tools for geoheritage identification and management, providing context for the methodological approach developed in this study.

These examples show that collaborative cartography can used in various spatial representation initiatives. From the data provided by collaborators who have empirical knowledge of the inhabited space, it becomes possible to identify recognized waterfalls that are already used for leisure and tourism practices and have a certain value for the community in question (Pereira Junior; Holanda & Spitz 2016).

Study Area

Covering an area of 1018.50 km², our study area encompasses the rural districts of the mountainous portion of the municipality of Pelotas and the entirety of the municipality of Arroio do Padre, understood as an enclave within the municipality of Pelotas (Fig. 1). This area is located between the geographical coordinates: 52º 36' 43.69" / 52º 12' 30.02" West Longitude and 31º 19' 20.72" / 31º 44' 06, 53" South Latitude, and is considered, according to Dutra (2016), to be the boundary between the Sul-Rio-Grandense Shield and the Gaúcha Coastal Plain. Verdum *et al.* (2004) understand the study area as a landscape unit called Serra dos Tapes. This area is located on the Uruguayan Sul-Rio-Grandense Plateau or Serra do Sudeste, with altitudes ranging from 100 to 400 m (Tomazelli & Villwock. 2000; Salamoni & Waskievicz 2013).

According to the 2019 map of Areas of Relevant Mineral Interest (ARIM), the study area includes the following lithological units: Dom Feliciano Suite, Cerro Grande Suite, Arroio Moinho Granite and Pinheiro Machado Intrusive Suite (Laux *et al.* 2019).

The Dom Feliciano Granitic Suite occurs sporadically, ca. 585 Ma (?) old, comprising equigranular leucogranites with a massive structure and elon-

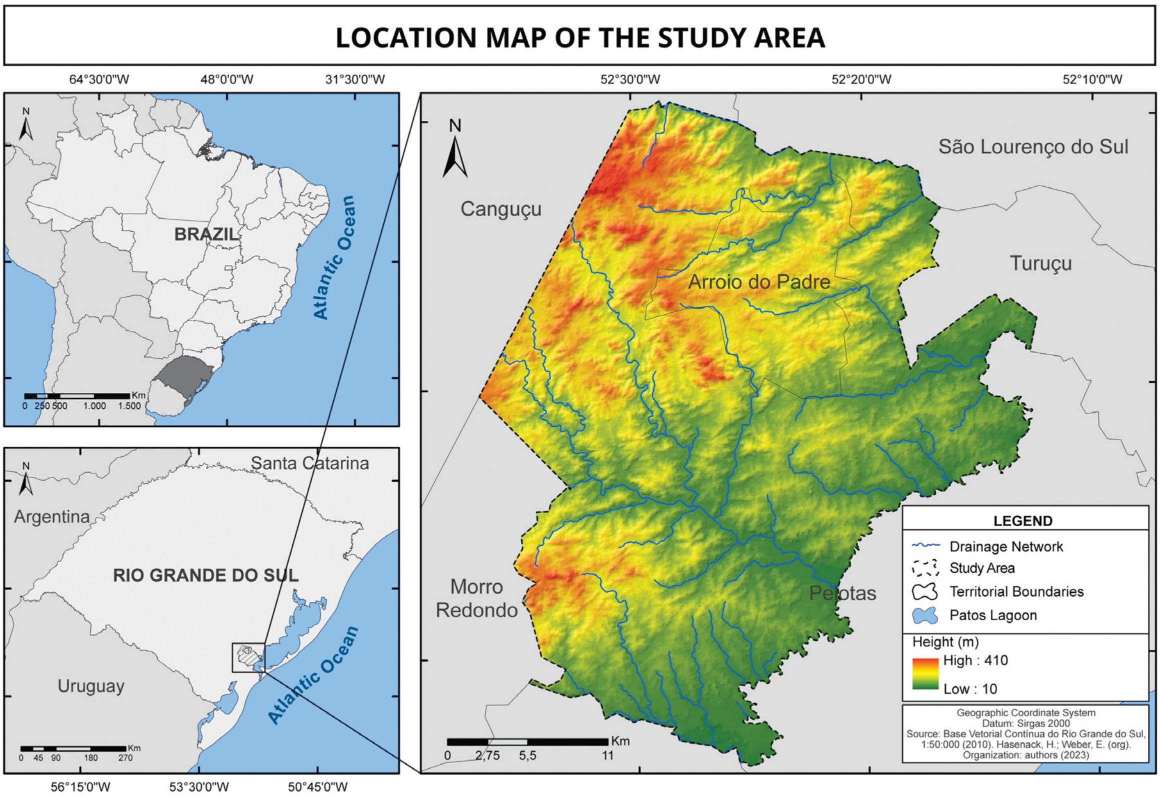

Figure 1. Location map. Source: Hasenack and Weber (2010).

gated shapes in a NE-SW direction (Philipp 1998). They can be found on the surface as abundant rock slabs, with light-colored and grayish, orange, beige and pink granites with a porphyritic texture (Viero & Silva 2010).

In the northeast of the area is the Cerro Grande Suite, ca. 585 Ma, which is characterized as a monzogranite with a porphyritic texture (Laux, *et al.* 2019). The CPRM (Viero & Silva 2010) understands this unit as an undeformed rock, which is arranged in the field in the form of *matacões*, or as slabs, which are often sold and exploited.

In the north of the study area is the Arroio Moinho Granite, which shows magmatic crystallization that occurred around 595 +-1 Ma, and has a composition that varies from syeno to syeno porphyritic monzogranite, with a grey to pinkish color, which exposes megacrystals of alkali feldspars, with an average size of 3 to 8 cm, inserted in a pink granulated matrix (Philipp 1998; Viero & Silva 2010). They show a pronounced foliation that displays phenocrysts and mineral stretching in the matrix, which are mainly present in the outer portions of the body. There are also shear zones and the occurrence of foliated mylonites, which help in the spatial organization of topographic ridges in a humid environment and regulate the presence of waterfalls (Passarelli, Basei & Campos Neto 1993; Philipp 1998).

The Pinheiro Machado Intrusive Suite, dated to ca. 625 Ma, occurs throughout the study area, comprising an association of granitoids with an expanded composition with dominance of granodiorites (Laux *et al.* 2019; Philipp 1998). They show a large proportion of primary structures, especially irregular and discontinuous banding caused by schlierens of mafic minerals (Philipp 1998).

These geological formations create the structural conditions that favor waterfall formation through differential erosion and lineaments that control drainage patterns (Paganotto 2019). Areas with high potential for waterfalls develop predominantly on surfaces with significant slopes (20-45% to >45%), as well as locations that expose a significant diversity of landforms under the influence of a high density of lineaments. The lineaments present in the Pelotas Batholith are mainly related to the development of ductile transcurrent shear zones (Rivera 2019), which create the structural framework necessary for waterfall formation.

The vegetation cover is characterized as Semideciduous Seasonal Forest and Dense Ombrophilous Forest (Venzke 2012), which contributes to the scenic beauty and ecological value of the waterfall sites. The physical-environmental characteristics, combined with the socio-economic context of the study area, have contributed to the tourist use of the waterfalls.

The study area is a culturally diverse territory, with multiple ethnic-cultural elements, including indigenous, African, Portuguese, and Germanic influences. This cultural diversity has contributed to residents valuing, emphasizing and preserving their customs and their respective identities, including their relationship with natural elements such as waterfalls (Ribeiro & Ávila 2018; Paganotto 2022). Local populations have based their social organization and respective ways of life on these natural environments, initially using the water courses for consumption and motive power. Over the years, the streams and rivers have also been used by tourists for leisure activities, representing a transformation in the purpose and value attributed to these geoheritage elements (Paganotto 2022).

The hydrological and climatic context of the study area is fundamentally influenced by the El Niño-Southern Oscillation (ENSO) phenomenon, particularly La Niña events, which significantly modulate regional precipitation patterns in Rio Grande do Sul state. According to climatological records from the Pelotas Agroclimatological Station (Embrapa/ UFPel/ INMET partnership) for the period 1971/2000, the region exhibits a humid subtropical climate without a defined dry season, with mean annual precipitation of 1,366.9 mm and February typically representing the wettest month with an average of 153.3 mm (UFPel 2025).

The 2019/2020 period was characterized by one of the most severe drought events recorded in Rio Grande do Sul, with hydrological deficits varying between -21.8% and -51.9% during the November 2019 to April 2020 semester compared to mean values. During the critical February-April 2020 trimester, precipitation variations ranged from -55.2% to -72.7% below normal values (IRGA 2020; Pelinson & Fan 2023). This extreme drought event was associated with La Niña conditions, which typically reduce precipitation totals across the southern region of Brazil, leading to extended periods of water scarcity that significantly impact regional hydrology and river discharge patterns.

Specific meteorological conditions during the fieldwork period (February 16–18 2022) were documented by the Capão do Leão meteorological station (Pelotas) – Code A887, which recorded mean air temperatures of approximately 23°C (Instituto Nacional de Meteorologia - INMET 2025). No precipitation was registered in the days immediately preceding the fieldwork, but on February 4, 5, and 6, the station recorded 37.6 mm 1.2 mm, and 3.4 mm of rainfall, respectively (INMET 2025). These records are consistent with field observations, which confirmed reduced precipitation in November and December 2021, with monthly totals of only 48.2 mm and 35.4 mm (INMET 2025). Cardoso (2021) observes that, although total precipitation increased in January, its hydrological effects are generally short-lived, typically persisting only until the end of that month.

Consequently, extended periods of water scarcity prevail, extending beyond the climatologically dry season. Further, we confirm that in both 2012 and 2019, reduced rainfall similarly led to pronounced water shortages.

The prolonged water scarcity observed during 2019/2020 directly impacted the discharge of regional watercourses, including the waterfalls inventoried in Pelotas and Arroio do Padre municipalities. During fieldwork conducted in February 2022, empirical observations confirmed significant reductions in waterfall discharge, contrasting markedly with expected conditions for February, when waterfalls would typically exhibit higher volumes. The drought conditions were so severe that 416 municipalities in Rio Grande do Sul declared states of emergency due to water scarcity by March 31 2022 (SOS Estiagem 2022), with many regional reservoirs reaching critically low levels or complete depletion.

The reduced discharge observed during the field campaign was important for the geomorphological characterization of the inventoried waterfalls, as they vary significantly depending on whether river discharge is a trickle or a torrent. The low-flow conditions during February 2022 underscores the importance of considering seasonal and interannual hydrological variations when characterizing water-related geoheritage elements, particularly in regions subject to significant climatic oscillations such as those influenced by ENSO phenomena.

Methodology

To establish the theoretical foundation for this study, we conducted a comprehensive literature review encompassing monographs, dissertations, theses, books, conference proceedings, and journal articles in both digital and print formats. The literature search was conducted between 2020 and 2024 using the following keywords: geodiversity, geoheritage, geotourism, waterfalls, and collaborative cartography. This review informed the development of our collaborative mapping methodology and provided the conceptual framework for integrating VGI approaches with geoheritage inventory practices.

The collaborative mapping approach was implemented through a structured online questionnaire using the Google Forms platform, titled 'Cachoeiras Costa Doce Form'. The questionnaire design followed established principles for VGI data collection (Pedregal *et al.* 2024), incorporating both mandatory and optional components to maximize participation while ensuring data quality. The survey instrument comprised three core components:

(a) Waterfall Identification: Participants were required to provide the local or popular name of the waterfall, following Goodchild's (2007) principle that local knowledge often contains valuable toponymic information not captured in official databases.

(b) Spatial Reference Data: This section requested location information in multiple formats to accommodate varying levels of technical expertise among participants. Accepted formats included: (i) geographical coordinates (decimal degrees or degrees/minutes/seconds); (ii) Google Maps addresses or links; (iii) any other spatial reference data compatible with GIS environments. This flexible approach aligns with recent advances in VGI methodology that emphasize accessibility and inclusivity in data collection (Pedregal *et al.* 2024).

(c) Visual Documentation: An optional section allowed participants to submit photographs of the waterfalls. This component served dual purposes: enhancing the inventory with visual records and providing a mechanism for preliminary data validation, as photographs could be cross-referenced with field observations.

The questionnaire design incorporated quality assurance measures recommended by recent VGI literature, including clear instructions, standardized terminology, and multiple validation checkpoints to minimize data entry errors and improve overall data quality (Pedregal *et al.* 2024). The collaborative mapping process was implemented in two distinct phases in response to COVID-19 pandemic constraints that necessitated remote data collection approaches.

Phase 1 (December 2020 - March 2021): The initial phase employed a broad recruitment strategy utilizing social media platforms to maximize reach and participation. The questionnaire was disseminated through: (i) dedicated Instagram profile (@cachoeirascostadoce) (Fig. 2); (ii) Facebook groups targeting hikers, rural tourists, and university students from the southern region of

TRANSLATION	
A	Do you know or have visited any waterfalls in Pelotas or Arroio do Padre? Tell us!
B	We want to know where the waterfalls are in Pelotas and Arroio do Padre. Can you tell us if you have been to or seen anything from large waterfalls and cascades, to jumps and rapids? Tell us! To help us, just access the email address below and respond to the form, which was created with the aim of locating and promoting tourism to the Pelotas and Arroio do Padre waterfalls. FORM LINK: https://forms.gle/gs6EfteXmpBz9ddNA If you have any questions and/or want to get in touch, you can find us on Instagram: @cachoeirascostadoce or send an email to: cascadescostadoce@gmail.com

Figure 2. Publication template used to publicize the form. Source: Cachoeiras Costa Doce (2021); Canva (2024).

Rio Grande do Sul; and (iii) WhatsApp messaging groups. This approach aligns with contemporary VGI practices that leverage social media networks for participant recruitment (Pedregal *et al.* 2024).

Phase 2 (September - October 2021): The second phase implemented a targeted recruitment strategy designed to address geographical gaps identified in Phase 1 data. This phase specifically focused on engaging participants from isolated districts and communities in northern and northeastern areas of the study region.

The selection of key collaborators in Phase 2 followed established principles for identifying local knowledge holders and community influencers in participatory mapping projects. Selection criteria included:

(i) Community Leadership Roles: Individuals holding formal or informal leadership positions, including school principals, teachers, and community representatives, were prioritized based on their established networks and credibility within local communities.

(ii) Local Knowledge Expertise: Participants with demonstrated familiarity with local landscape, including members of hiking groups, rural tourism operators, and long-term residents, were specifically targeted for their potential to provide accurate spatial information.

(iii) Communication Network Access: Individuals with access to local communication networks, including participants in online community groups, local commerce networks, and recreational organizations, were selected for their ability to disseminate the survey to broader community networks.

(iv) Geographic Representation: Selection prioritized individuals from under-represented geographical areas identified through spatial analysis of Phase 1 responses, ensuring comprehensive coverage of the study area.

These "influential individuals" functioned as "seed" participants, following the network diffusion model commonly employed in VGI projects to maximize geographical and demographic coverage while maintaining data quality standards (Pedregal *et al.* 2024). The validation of collaboratively collected data followed a multi-stage approach designed to ensure spatial accuracy and minimize false positives while maintaining the participatory nature of the methodology.

Stage 1: Digital Validation and Spatial Analysis. Collected data were initially processed and validated through digital analysis using Microsoft Excel 2016 for tabulation and quantification. Spatial coordinates and location references were converted to standardized point data and imported into Google Earth for preliminary spatial validation. This process identified obvious spatial errors, duplicate entries, and locations outside the study area boundaries.

Stage 2: Cross-Validation Through Collaborative Consensus. Following established VGI quality assurance practices, we implemented a cross-validation approach where multiple independent reports of the same waterfall were compared for spatial and descriptive consistency. Waterfalls receiving multiple mentions from different participants were considered to have higher reliability, while single-mention locations were flagged for additional verification during field validation.

Stage 3: Field Validation and Ground-Truthing. Comprehensive field validation was conducted on February 16-18 2022, serving both as an inventory method and as the final validation stage for collaborative data. Field validation employed:

(i) GPS Verification: Precise spatial coordinates were collected using Garmin Montana™

650 GPS equipment to verify the accuracy of collaboratively provided location data.

(ii) Photographic Documentation: Systematic photographic records were obtained for comparison with participant-submitted images, providing visual validation of waterfall identification and characteristics.

(iii) Aerial Imagery Collection: DJI Mavic 2 Pro unmanned aircraft was employed to obtain aerial perspectives for comprehensive documentation and to verify accessibility and landscape context information provided by participants.

Stage 4: Inventory Assessment and Characterization. The validated waterfalls were subjected to systematic assessment using an expeditious inventory method adapted from established geosite evaluation frameworks (Bento & Rodrigues 2010; Oliveira *et al.* 2017; Ziemann 2016). The assessment form was initially tested at Cascatinha waterfall (52º 30' 53.089" W, 31º 37' 39.043" S), which served as a pilot site for methodology refinement.

The inventory assessment evaluated five criteria using a standardized scoring system (1-low 2-medium, 3-high):

(a) Access: Evaluation of accessibility factors, including parking availability, proximity of access points, and distance from arrival points to waterfalls.

(b) Cultural, Historical, and Religious Relationships: Assessment of material and intangible cultural manifestations, including chapels, religious offerings, and historical significance related to territorial formation processes.

(c) Infrastructure: Evaluation of visitor support facilities, including waste disposal systems, accommodation options, and commercial services availability.

(d) Environmental Preservation: Assessment of site conservation status using field-defined categories (degraded, moderately degraded, or preserved).

(e) Scenic Attractiveness: Subjective evaluation considering water flow characteristics, vegetation relationships, visual pollution presence, and bathing suitability.

This multi-stage validation approach ensured that the final inventory represented a synthesis of community knowledge validated through scientific field assessment, addressing key concerns about VGI data quality while maintaining the participatory benefits of collaborative mapping approaches.

Results

Using Collaborative Cartography to Identify and Recognize Waterfalls in Pelotas and Arroio do Padre

Collaborative mapping enabled the identification of 17 waterfalls during the first phase of the investigation from the participation of 70 collaborators, five of whom provided photographs, and confirmed the significance of four prominent waterfalls: Arco-Íris, Camboatá, Imigrante, and Paraíso. The second stage saw the participation of 36 collaborators, who shared 13 images –, who nominated 03 new waterfalls, as can be seen in Table 1.

The second stage of the questionnaire was carried out by expanding the list of collaborators, highlighting the more isolated districts and communities in the municipality of Pelotas, such as the 4th Triunfo District and the 6th Santa Silvana District, located in the north and northeast of the study area. During this process, three more waterfalls were added to the list:

a) Belfiore Camping e Lazer Waterfall - owned by the Camelatto family - has a wine produc-

Table 1. Waterfalls identified through Collaborative Cartography

WATERFALL IDENTIFICATION	FIRST STAGE NOMINATIONS	SECOND STAGE NOMINATIONS	ACCUMULATED FROM THE TWO STAGES
Imigrante Waterfall	18	7	25
Rainbow Waterfall	14	4	18
Camboatá Waterfall	9	5	14
Paraíso Waterfall	7	7	14
Pousada do Moinho Waterfall	5	0	5
Três Cerros Waterfall	3	1	4
Corvo Waterfall	0	1	1
Pegoraro Waterfall	2	2	4
Camping Moinho das Pedras Water-fall	2	1	3
Antigo Moinho Dona Ana Waterfall	1	0	1
Kaster Stream Waterfall	1	0	1
Santa Coleta Waterfall	1	0	1
Camping Sítio Paraíso Waterfall	1	0	1
Recanto das Águas Waterfall	1	0	1
Recanto Ecológico Waterfall	0	1	1
Cascatinha Waterfall	1	2	3
Belfiore Camping e Lazer Waterfall	0	2	2
Templo das Águas	1	0	1
*Amoreza Site (Morro Redondo)	2	1	3
*Cachoeira Guesthouse (Morro Redondo)	1	2	3
WATER FALLS IDENTIFIED	TOTAL INDICATIONS FOR EACH PHASE		TOTAL
18	70	36	
TOTAL		106	

tion unit near the leisure and tourism area;

b) Corvo, Waterfall a well-known destination for trekkers due to its difficult access;

c) Recanto Ecológico Waterfall, a villa belonging to the Guterres family, whose aim is to open up their home to conscientious visitors and tourists who want to enjoy leisure activities and admire the biotic and abiotic elements in a responsible way.

In addition, among the waterfalls mentioned by collaborators during the two stages of collaborative mapping, four stand out: Imigrante Waterfall, with 25 mentions; Arco-Íris Waterfall, with 18 mentions; and Paraíso Waterfall, with 14 mentions, all located in the municipality of Pelotas. Camboatá Waterfall was also identified with 14 mentions, belonging to the rural area of the municipality of Arroio do Padre (Table 1).

In view of the data presented, 79 people took part

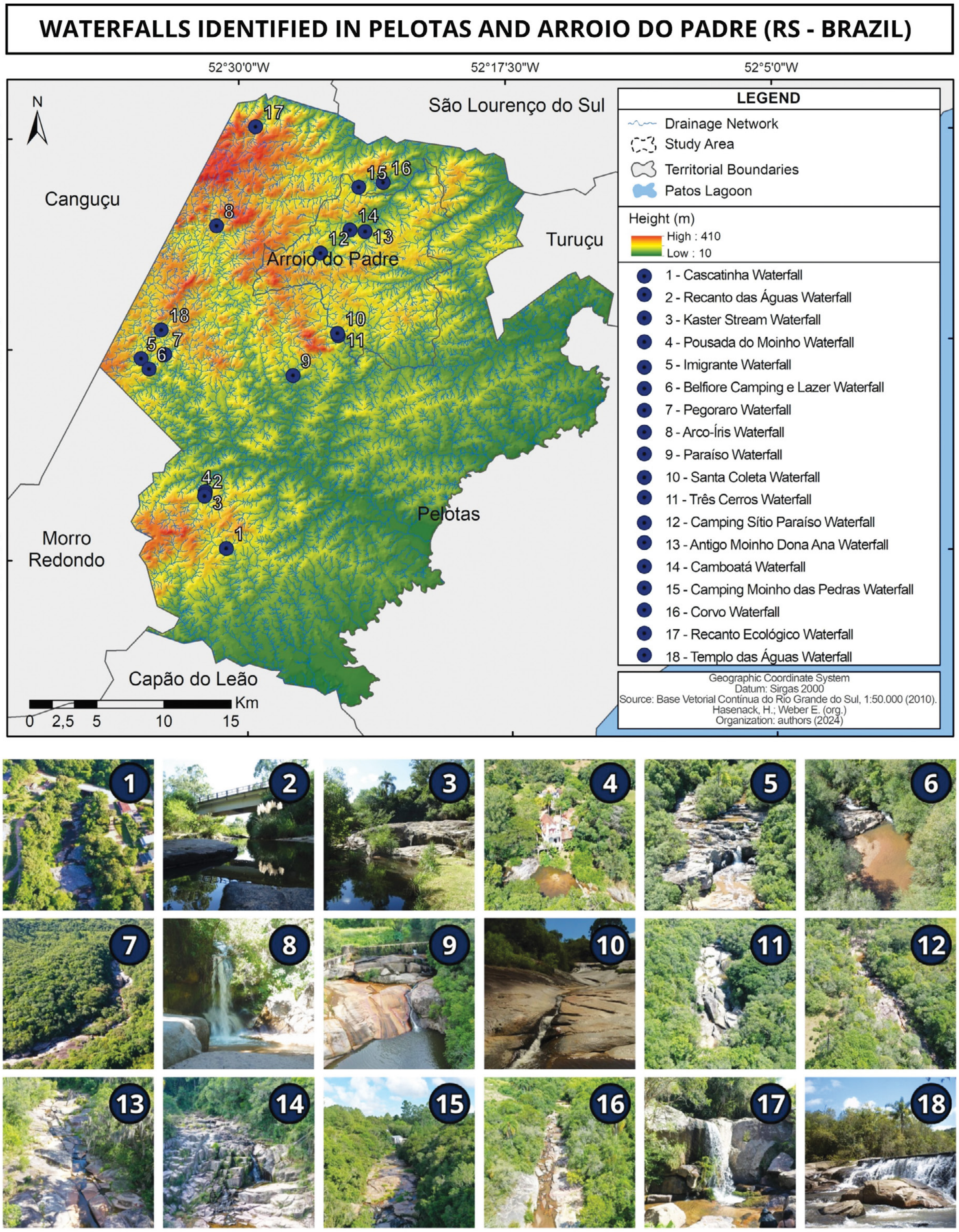

Figure 3. Waterfalls identified in Pelotas and Arroio do Padre (RS). Source: Hasenack and Weber (2010), Cruz (2012) and personal collection (2024).

in the collaborative mapping and 20 recommendations for waterfalls were recorded, with approximately 106 mentions. However, two of these relate to properties located in the municipality of Morro Redondo, a territory not included in the study area (Table 1). As a result then, 18 waterfalls were identified in Pelotas and Arroio do Padre (Fig. 3).

Notably, the waterfalls receiving the highest number of mentions represent features already recognized by local and regional communities. The five waterfalls most recognized by the survey subjects have parking lots, areas for dining and lodging, bathing facilities, and spaces for selling colonial and industrial products on the rural properties where they are located. Additionally, there is the possibility of overnight stays through campsites (Imigrante and Paraíso Waterfall) or room rentals (Pousada do Moinho Waterfall).

The Arco-Íris and Camboatá waterfalls, on the other hand, do not allow tourists to stay overnight due to concerns about the degradation of the waterfall and the surrounding area. However, it should be noted that there is no stipulated maximum number of tourists and visitors allowed on the site, leading to the underutilization of the activities proposed by the owners due to overcrowding. The waterfalls most mentioned by the collaborators (Fig. 4) can be considered geoheritage in the municipalities of Pelotas and Arroio do Padre from their recognition by individuals who enjoy the natural features of these waterfalls (Paganotto 2022, Paganotto et al. 2022).

The other waterfalls had fewer than five mentions, indicating limited knowledge among individuals about the location and potential of these areas (Table 1).

Our methodology satisfactorily achieved the established objective, with a significant highlight being the identification of waterfalls, cascades, streams, and jumps located to the northeast and north of the study area, which were not covered in the first stage of collaborative mapping.

We found that the implementation of our program through social media platforms presented limitations in data collection, as small municipalities and rural areas encountered significant barriers to internet access (Viero & Silveira 2011). These challenges encompassed inadequate physical transmission infrastructure, insufficient appropriate equipment, limited connectivity options, and lack of training for effective use of digital platforms (Viero & Silveira 2011).

We noted that most collaborators were tourists and visitors to the properties where the waterfalls are located, basing their knowledge on the waterfalls recognized by the local and regional population. Hikers played a significant role, helping to identify waterfalls that are difficult to access.

Inventory of Waterfalls Identified Through Collaborative Cartography: Subsidies for Geotourism

Eighteen waterfalls were identified using collaborative cartography in the municipalities of Pelotas and Arroio do Padre, but only 17 of them were analyzed based on five criteria covering physical-natural and historical-cultural information about the landscape where the geopatrimonial elements are located (Table 2).

One aspect arising from the articulation of abiotic elements refers to defining a waterfall according to its shape and volume. In fact, nine waterfalls in Pelotas and Arroio do Padre can be characterized as cascades and streams, since the drainage network of these waterfalls covers the entire bedrock and presents a series of steps with a relatively low angle (Plumb 2005; Luerce 2015).

Two examples, Recanto das Águas Waterfall and Belfiore Camping e Lazer Waterfall (Paganotto 2022), are in streams, here understood as rivers

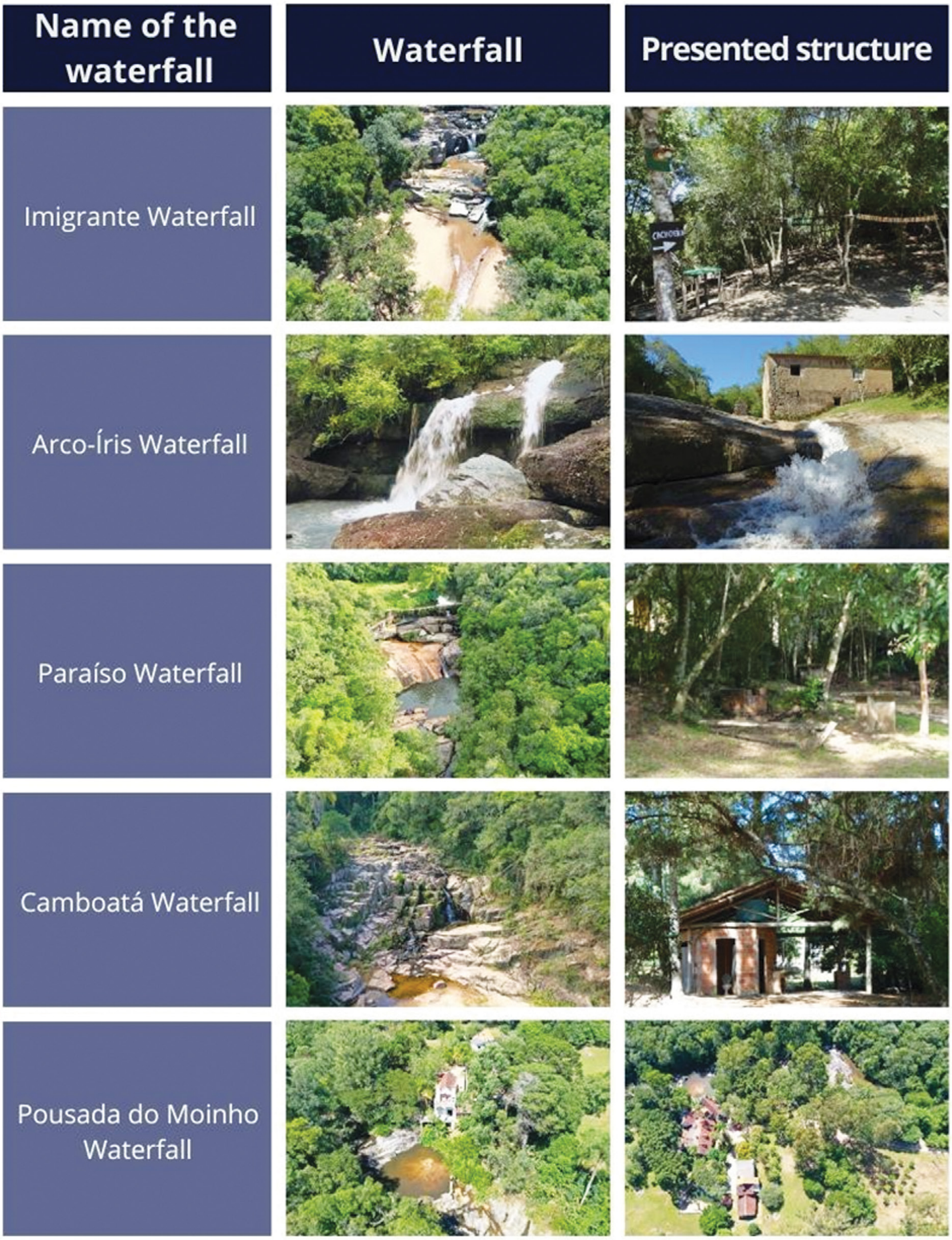

Figure 4. Structures of the properties most cited by collaborative mapping actors. Source: Authors (2024).

Table 2. Items evaluated in the inventory of the Pelotas and Arroio do Padre waterfalls: A) Popular name; B) Location; C) Type (Plumb 2005, Luerce 2015); D) Mentions in collaborative cartography; E) Access; F) Relationship with cultural, historical and religious aspects; G) Infrastructure; H) Scenic attractiveness and beauty; I) Environmental Preservation.

General Characteristics				**Collaborative Cartography and Field Trips (Quick Survey Application)**					
Nº.	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
1	Cascatinha Waterfall	Pelotas (52º 30' 53, 089" W/ 31º 37' 39,043" S)	Waterfall	3	High	High	Low	Medium	Medium
2	Recanto das Águas Waterfall	Pelotas (52° 31' 52, 52" W/ 31° 35' 31, 75" S)	Rapid	1	High	Medium	Medi-um	High	High
3	Kaster Stream Waterfall	Pelotas (52° 31, 59" W/ 31° 35' 27, 98"S)	Block	1	Medi-um	Low	Low	High	High
4	Pousada do Moinho Waterfall	Pelotas (52°31' 50, 43" W/ 31° 25' 20, 73" S)	Fan	5	High	High	High	High	High
5	Imigrante Waterfall	Pelotas (52° 34' 46, 18" W/ 31° 29' 56, 15" S)	Waterfall Slide or Rapid	25	Medi-um	Low	Medi-um	High	Medium
6	Belfiore Camping e Lazer Wa-terfall	Pelotas (52° 34' 24, 188" O/ 31° 30' 21, 982" S)	Rapid	2	High	High	High	Medium	Medium
7	Pegoraro Waterfall	Pelotas (52° 33' 39, 342" W/ 31° 29' 46, 941" S)	Horse Tail and Slide or Rapid	4	Medi-um	Low	Low	High	High
8	Arco-Íris Waterfall	Pelotas (52° 31' 8, 30" W/ 31° 24' 37, 124 64" S)	Dive	18	High	High	High	High	Medium
9	Paraíso Waterfall	Pelotas (52° 27' 37, 73" W/31° 30' 42, 41" S)	Segment-ed	14	Medi-um	High	High	High	High

10	Santa Coleta Waterfall	Pelotas (52° 25' 30, 924" W/ 31° 29' 2, 025" S)	Fan	1	Low	Low	Low	High	High
11	Três Cerros Waterfall	Pelotas (52° 25' 28, 906" W/ 31° 29' 7,805" S)	Fan	4	Low	Low	Low	High	High
12	Camping Sítio Paraíso Waterfall	Arroio do Padre (52° 26' 16, 8" W/ 31° 25' 47 1" S)	Slide or Rapid	1	Medium	Low	Low	Medium	High
13	Antigo Moinho Dona Ana Waterfall	Arroio do Padre (52° 24' 09, 7" W/ 31° 24' 56, 7" S)	Slide or Rapid	1	High	High	Low	Medium	Medium
14	Camboatá Waterfall	Arroio do Padre (52° 24' 51, 891" W/ 31° 24'49, 94"S)	Slide or Rapid	14	High	Low	High	High	High
15	Camping Moinho das Pedras Waterfall	Pelotas (52° 24' 25, 674" W/ 31° 23' 8, 918" S)	Slides or Rapid	3	High	High	High	Medium	High
16	Corvo Waterfall	Pelotas (52° 23' 17, 2" W / 31° 22' 58, 2" S)	Slide	1	Low	Low	Low	Medium	Medium
17	Recanto Ecológico Waterfall	Pelotas (52° 29' 12, 391" W/ 31° 20' 40, 293" S)	Dive	1	Low	Low	Low	High	High

with low water flow and small obstacles in their beds. One example shows a watercourse covering the entire rocky bed, Cachoeira do Arroio dos Kaster (Plumb 2005; Luerce 2015). Three examples (Pousada do Moinho Waterfall, Santa Coleta Waterfall, and Cachoeira Três Cerros Waterfall) arefan-shaped waterfalls, with a sub-vertical block of bedrock and a large jet of water that increases towards the plunge pool (Plumb 2005; Luerce 2015). Pegoraro Waterfall can be classed as a ponytail waterfall, with its sub-vertical drop and considerable contact with the bedrock (Plumb 2005).

There are also two vertical waterfalls that lose contact with the bedrock surface: Arco-Íris Waterfall and Recanto Ecológico Waterfall (Plumb 2005). Further, Paraíso Waterfall is classed as a segmented waterfalls, with a watercourse that is segmented and divided into at least two parallel bands. Finally, Camboatá Waterfall is a step or layered waterfall, showing water falling down a series of steps, with the last two layers of the bedrock visible (Plumb 2005; Paganotto 2022).

The inventory form (Table 2) was also used to analyze access conditions, including the presence of paved roads, adequate signage, proximity to bus stops and transport lines, proximity to the municipalities of Pelotas and/or Arroio do Padre, and the distance between the property's parking lot and the waterfall. Eight of the inventoried waterfalls have a high access value, especially Cascatinha, Recanto das Águas, and Pousada do Moinho, which are located close to the municipality of Pelotas, on the banks of the BR-392 - Federal Highway of Rio Grande do Sul (Brazil). The other waterfalls had medium and low scores for access. The Corvo and Recanto Ecológico waterfalls achieved low scores, as they are located to the north in the municipality of Pelotas, and access to them is via trails.

As for the relationship that the waterfalls have with cultural, historical, and/or religious aspects, seven waterfalls scored highly for having old mills, chapels, or offering areas in their vicinity. This is the case with Cascatinha, which, as well as being a place for leisure and tourism, is also a place for worshipping African entities, such as 'Xangô', the orisha of justice, who is associated with rock, as well as 'Oxum', who is associated with fresh water, exhibiting a high degree of relationship with the cultural, historical, and religious aspects of the municipality of Pelotas.

The waterfalls Pousada do Moinho, Arco-Íris, Paraíso, Antigo Moinho Dona Ana, and Camping Moinho das Pedras have old mills on the banks of the rivers, which have changed their purpose from generating energy and motive power to becoming places for selling food products, lodging, and/or just decorating the landscape. The Belfiore Camping e Lazer property scored highly because the owners promote cultural and historical aspects related to Italian immigration in Pelotas, with emphasis on grape growing, juice production, wines, and colonial foods—all products traditionally processed on the farm. The other waterfalls received an average and low rating for this item from the absence of material elements or practices by local communities.

The infrastructure item aimed to assess the presence of spaces for leisure and recreation, the availability of garbage cans for the responsible disposal of waste generated by tourists and visitors, the possibility of lodging on the property or nearby, and the possibility of having a snack bar or market nearby. Only six waterfalls scored highly on this item, two scored medium, and nine waterfalls scored low, as can be seen in Table 2.

Attractiveness and scenic beauty were also evaluated. This includes the integrity of the landscape, as well as water flow, the relationship between the watercourses and the surrounding vegetation cover, the presence of solid waste, and the characteristics of the water (color, turbulence, and bathing). These characteristics helped in the high valuation of ten waterfalls and the medium valuation of seven waterfalls, cascades, and streams.

Finally, we looked at the environmental preservation of the waterfalls, including the presence of Permanent Preservation Areas (PPAs), the absence of furrows, gullies, silting of watercourses by agriculture, and the removal of vegetation, the presence of rubbish dumps, and the absence of anthropic action in watercourses. Eleven waterfalls were highly rated, with the remaining six waterfalls, cascades, and streams receiving average scores (Table 2).

The inventory form analysis revealed important patterns for geoconservation planning. Eight of the inventoried waterfalls have high access values, facilitating both tourism development and conservation monitoring. Seven waterfalls scored highly for cultural, historical, and religious relationships, indicating their importance as integrated natural-cultural heritage sites requiring specialized geoconservation approaches. The infrastructure assessment revealed that only six waterfalls scored highly, suggesting opportunities for sustainable development that balances tourism infrastructure with environmental protection. The attractiveness and scenic beauty evaluation resulted in high scores for ten waterfalls, indicating significant potential for geotourism development. Most importantly for geoconservation, eleven waterfalls received high scores for environmental preservation, demonstrating that much of the area maintains good conservation status. The typological diversity of waterfalls (including plunge, fan, horsetail, segmented, and cascade types) represents significant geodiversity that requires differentiated geoconservation approaches based on the specific geological-geomorphological characteristics and vulnerability of each type.

The inventoried waterfalls can be arranged into routes to support future geotourism itineraries. They are being used for environmental interpretation through the Instagram profile @cachoeirascostadoce. The page publishes content on the concepts of geodiversity, geoheritage, geotourism, and geoconservation. There are also regular posts about the waterfalls identified by this research, providing information in popular language about characteristics such as access, infrastructure, and environmental awareness messages for tourists who visit the waterfalls.

Future geotouristic itineraries should expand the aspects of environmental interpretation, also involving the understanding of the formation of the waterfalls and the environment in which they are located, with the aim of including the waterfalls identified in the wider understanding of the geological and geomorphological formation of the place visited.

Conclusions

The collaborative cartography methodology developed in this study demonstrates considerable potential for international application and replication. This approach illustrates how local community knowledge can be systematically integrated into scientific geoheritage inventories. Using social media platforms and digital technologies aligns with global trends in Volunteered Geographic Information (VGI) and collaborative mapping practices documented across diverse international contexts. The results contribute to the growing body of international knowledge on community-based geoheritage identification, offering a replicable framework that could be adapted to different cultural and geographical contexts.

The integration of local knowledge with scientific assessment, as demonstrated in this study, supports the development of more inclusive and comprehensive geoheritage inventories, contributing to international best practices in geoconservation and sustainable geotourism development. The methodology's effectiveness in identifying previously unknown geoheritage sites (such as Corvo Waterfall and Recanto Ecológico Waterfall) suggests its potential value for geoheritage discovery in other regions with similar geological and cultural characteristics. The approach could be particularly valuable in developing countries or regions with limited resources for systematic geoheritage surveys, as it leverages existing community knowledge and accessible digital technologies.

Further, the study's integration of cultural, historical, and religious aspects with geological-geomorphological assessment provides a model for holistic geoheritage evaluation that could inform international standards for geoheritage assessment. The recognition of waterfalls as complex geodiversity elements with multiple values (scientific, cultural, economic, aesthetic) aligns with international trends toward integrated approaches to geoheritage management that consider both natural and cultural heritage dimensions.

The methodology's emphasis on community engagement and local knowledge integration aligns with UNESCO's recommendations for participatory approaches to heritage management and could support applications for international geoheritage designations such as UNESCO Global Geoparks. The study also demonstrates the potential for collaborative cartography to support the United Nations Sustainable Development Goals, particularly those related to sustainable tourism (SDG 8), sustainable communities (SDG 11), and partnerships for the goals (SDG 17), by providing a framework for community-based sustainable development initiatives centered on geoheritage conservation and promotion.

There are limitations. The dependence on social media platforms for data collection may introduce selection bias, as participants may not adequately represent the demographic spectrum of local populations. Rural communities with restricted internet access will be underrepresented, despite targeted efforts in the second phase to include more geographically isolated districts. The digital divide, resulting from unequal access to the internet and technology, may have excluded waterfall owners and local knowledge holders from participating in the survey.

The waterfalls in the municipalities of Pelotas and Arroio do Padre require not only identification and inventory but also responsible management of the properties where they are located, as well as ongoing awareness campaigns for tourists and visitors. This proposal can be implemented through geo-educational activities, the creation of geotourism itineraries, and the application of tourist and interpretative signage. Awareness-raising is at an embryonic stage and is supported by social networks, through the Cachoeiras Costa Doce page (@ cachoeirascostadoce), which aims to publicize the waterfalls. There is the intention and commitment to continue publishing on the page, as well as turning it into a website. To effectively disseminate the results obtained, proposals should be submitted to the Municipalities of Pelotas and Arroio do Padre, specifically to their Departments of Development, Tourism, and Innovation.

Future research should focus on developing complementary strategies to include digitally excluded populations, implementing long-term monitoring protocols for the identified waterfalls, and establishing carrying capacity assessments for sustainable geotourism development. The integration of this methodology with formal geoconservation planning processes could enhance its contribution to systematic geoheritage protection and management.

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Authors' Contributions

Victória Dejan Paganotto led the writing of the manuscript and was responsible for the figures and data systematization, under the supervision of Adriano Luís Heck Simon. All authors critically reviewed the work, approved the final version, and agreed to be accountable for all aspects of the study.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest associated with this study.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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